

U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Simple Bouguer gravity anomaly map and geologic
interpretation; Iron River 1° by 2° quadrangle,
northern Michigan and Wisconsin

by

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This report is preliminary and has not been edited or reviewed
for conformity with U.S. Geological Survey standards
and nomenclature.

INTRODUCTION

This map and accompanying report is one of several geophysical, geological, and geochemical maps that are being prepared for the Iron River 1° by 2° quadrangle to assess the mineral potential of this region. In this report, we present a preliminary geologic interpretation of the gravity map and briefly consider some of the implications pertaining to mineral resources.

THE GRAVITY DATA

Source of and reduction of data

The Bouguer gravity map was compiled from approximately 5225 stations which came from a variety of sources as shown in table 1. All of the gravity data were either tied to or adjusted to conform with the 1971 Unified International Gravimetric Net (Morelli, 1974). Data were reduced to the simple Bouguer anomaly using sea level datum, the 1967 theoretical gravity formula for the equipotential ellipsoid (Int. Assoc. of Geodesy, 1971) and a density of 2.67 gm/cm^3 for the rocks between the ground surface and datum.

Table 1.--Sources of gravity data.*

<u>Source</u>	<u>Estimated number of stations</u>
Michigan Technological University	
L.O. Bacon (1957)	2008
W.N. Rognerud (1974)	192
J. Fredericks (1978)	167
U.S. Geological Survey	1832
Michigan State University	
W.R. Miller (1966)	294
B.A. Carlson (1972)	93
Defense Mapping Agency	180
Copper Range Exploration	175
Wright State University	161
K. Fredricks (1975)	
University of Wisconsin	
Various sources	<u>124</u>
Total number of Stations	5226

* The number of Stations shown for each data set does not necessarily represent all of the data available from that source. For example, only 192 Stations were used from Rognerud's data, even though there are many more stations in his data sets.

Accuracy of gravity data

Accuracy of the gravity data is variable as shown by solid and dashed contours on the map and by different symbols for the gravity stations. Most data are accurate to ± 0.3 milligal according to a U.S. Geological Survey code for accuracy of gravity data established Robbins and others (1974). Two data sets from the southwest part of the quadrangle in Wisconsin either have exceedingly high drift (as much as 2 milligals per base loop) or differ from older data sets as much as 2 milligals on some duplicate stations. For this reason, the older data sets were used in contouring and the newer and less accurate data sets were used where there were gaps in coverage of older data. Note the dashed contours in the southwest corner of the map.

Similarly, in the Porcupine Mountain region of Michigan (the northwest quadrant of the map) some of the stations which have duplicate gravity readings differ in observed gravity by as much as one milligal. Thus, the contours are also dashed in this area. Elsewhere, duplicate readings agree within a few tenths of a milligal. Contours are solid in these areas to indicate more reliable data.

All of the accuracy coded gravity data used in compilation of this map will soon be available on magnetic tape through the World Data Center for Solid Earth Geophysics.

GEOLOGIC INTERPRETATION OF GRAVITY DATA

Background geology

An open-file map showing a preliminary version of the bedrock geology in the Iron River quadrangle has been published by Cannon (1978). His map shows that there are three major ages in rocks in the area: Archean, Proterozoic X, and Proterozoic Y and Z. The distribution of these three major rock units are shown in figure 1a. In addition, figure 1a also shows some of the major structural features to be discussed in this report.

A sequence of Keweenaw clastic units comprises the youngest rocks in the quadrangle. These include upper Keweenaw Jacobsville Sandstone, Freda Sandstone, Nonesuch Shale, and Copper Harbor Conglomerate, all of which have a low density relative to other rocks in the area as shown on Table 2. The Jacobsville Sandstone fills a large basin which extends southwest from the Keweenaw Bay. It is bounded on the northwest by the Keweenaw fault.

Keweenaw volcanic rocks, most of which are stratigraphically below the clastic units, underlie most of the northwest part of the map. They include the volcanic rocks of the Unnamed formation, Portage Lake Volcanics, and the volcanic rocks of the Siemens Creek and Kallander Creek Formations. The volcanic rocks are mainly mafic in composition with minor amounts of felsic rock. However, according to Hubbard (1975), the upper part of the upper Keweenaw volcanic sequence (Unnamed formation) is more felsic than the lower part (Portage Lake Formation).

Proterozoic X rocks lie unconformably above Archean basement rocks. For the most part, they consist of metagraywacke and slate with relatively minor amounts of dolomite, quartzite, and conglomerate. Economically important deposits of cherty iron-formation and ferruginous slates are intercalated with Proterozoic X strata. Metavolcanic units, ranging from mafic to felsic in composition, occur in the southeastern and western parts of the quadrangle as shown on figure 1a.

Table 2 shows that the graywacke and slate, which form the bulk of the Proterozoic X section, have densities that are very close to those of the underlying Archean gneiss. But the presence of iron-formation generally makes the bulk density of the Proterozoic X section greater than the density of Archean basement. Also, except where they are felsic, the Proterozoic X volcanic rocks are generally denser than Archean basement rocks.

Archean rocks range in composition from granite to intermediate and mafic gneiss. A boundary between two Archean terranes, recently discovered in the Lake Superior region by Morey and Sims (1976); Sims (1976); and Morey (1978), divides granite-greenstone terrane on the north from gneiss terrane on the south. A gravity study by Klasner and Sims (1979) in the western part of the quadrangle, suggests that the overall density of the upper part of the Archean crust is greater south of the boundary than north of it. Local variations in composition of the gneiss as well as the presence of relatively dense amphibolitic zones in either terrane cause variations in this density model.

Table 3 shows that the Precambrian rocks of the area have undergone a long and complex tectonic history. Several important features formed as a result of tectonism. These include the 1.1 b.y. old Keweenaw fault, thick sequences of basalt, the trough in which the Jacobsville Sandstone is deposited, and major Proterozoic X troughs and basins, such as the Marquette trough and Michigamme basin which formed during Penokean orogeny 1.9 b.y. ago (Cannon and Klasner, 1972; Cannon, 1973; and Klasner, 1978). In the southwestern part of the quadrangle, Archean crust has been remobilized to form gneiss domes (Sims and Peterman, 1976). Recent studies by Klasner and others (1979) show that the Archean rocks of the Canadian Shield possesses regional zones of weakness and faults which predated and controlled the orientation and location of later structural features such as the Keweenaw rift and possibly some of the Proterozoic X basins. Several of these zones cross the Iron River quadrangle.

DISCUSSION OF THE GRAVITY MAP

The most prominent feature on the Bouguer gravity anomaly map and on the isometric diagram of the Bouguer gravity surface (fig. 2) is a series of northeast trending gravity anomalies with wavelengths of about 40 km. Over Proterozoic Y and Z (Keweenawan) terrane the anomalies have amplitudes in excess of 100 milligals and are caused by the juxtaposition of dense volcanic rocks and less dense sedimentary rocks. Over Proterozoic X and Archean terrane these anomalies are more subdued and are parallel to the trend of the Penokean fold belt. Although the anomalies from the two terranes are roughly parallel in this area, the gravity map of the northern Michigan-Lake Superior region (Klasner and others, 1979) shows that east and west of the Iron River quadrangle the gravity anomalies over the Keweenawan rift cut across the long wavelength anomaly associated with the Penokean fold belt.

Numerous gravity anomalies, gradients and lineations are present on the Bouguer gravity map. These are outlined on figure 1b and discussed as follows:

A. Thick sequences of relatively dense Keweenawan basalt cause the large positive gravity anomaly. A₁ marks the position of lower Keweenawan basalt that lies in contact with Proterozoic X rocks (Hubbard, 1975). They have relatively little gravity expression at this scale.

B. This gravity low lies above the Porcupine Mountain Syncline. An unpublished map by White shows that the Nonesuch Shale and Copper Harbor Conglomerate which fills the syncline is only a few thousand feet thick. A modelled gravity profile (Figure 3) shows that the low density shale and conglomerate cannot cause the large negative gravity anomaly in this area. White (personal communication) has suggested the Porcupine Mountain Syncline may be a collapse caldera and the gravity low may be caused by a low density volcanic pipe beneath the syncline. The gravity model shown in figure 3 supports this concept. This would mark one of the volcanic centers in the Lake Superior region as proposed by White (1972).

C. This steep, 6 milligals per km, gravity gradient is associated with the Keweenaw fault which places dense basalt on the north adjacent low density Jacobsville Sandstone on the south. Note that the gradient is offset by numerous northwest trending faults.

D. This low amplitude positive gravity anomaly is within the gravity low (E) associated with the Jacobsville basin. It is interpreted to mark the position of a ridge of lower Keweenawan basalt which lies beneath Jacobsville Sandstone. Rognerud (1974) has shown that at the widest part of the ridge, horsts of basalt lie within 150 meters below ground surface.

E. This pronounced gravity low is caused in part by a trough of low density Jacobsville Sandstone. Bacon (1966) has suggested from gravity and magnetic data that the trough is graben with up to 3 km of Jacobsville Sandstone overlying Keweenawan basalt.

Proterozoic X

F. This is an area of positive gravity relative to adjacent areas. The positive gravity is caused by Proterozoic X sedimentary rocks that are generally denser than underlying Archean basement. The positive anomaly at F_1 is caused by dense iron-rich rocks of the Marquette trough. However, where the sediments are black slate and quartzite with little, if any, iron-formation, such as at F_2 , there may be only a small density contrast between them and the basement, and therefore little, if any, gravity expression. The cause of the triangular shaped gravity low at F_3 is not known. Foose (personal communication) has suggested that it may be caused by up to 6000 m of lower Proterozoic slate and graywacke.

G. These positive gravity anomalies mark the position of iron-rich Proterozoic X sedimentary rocks. G_1 is the Iron River district. G_2 and G_3 probably mark basins of iron-formation, but, to the best of our knowledge, the deposits have not been confirmed by drilling.

H. This gravity low marks the occurrence of a subjacent granitic pluton. The pluton is most likely Proterozoic X in age because Archean rocks in this area south of the boundary between greenstone terrane and gneiss terrane are relatively dense gneisses of granitic to intermediate composition that could not cause such a gravity low. Also, Proterozoic X plutons have been mapped in Wisconsin (Sims and others, 1978) just south of this area.

Archean

I. This gravity low overlies the Puritan Quartz Monzonite pluton which lies within granite-greenstone terrane north of the Great Lakes Tectonic Zone.

J. These areas mark the position of Archean gneiss domes. They are not always obvious on the gravity map but careful examination of the map shows that most of the domes have lows above them.

K. This area is underlain by block faulted Archean gneiss which has shallow basins of Proterozoic X sedimentary rocks between hosts of Archean rocks. (See Cannon and Klasner, 1976).

K₁ marks the position of the Hemlock volcanic which surround a core of Archean gneiss K_A. A two-dimensional gravity model has been constructed by Foose (personal communication) extending southwest from K_A. It shows that the Hemlock volcanic rocks may be about 6000 m thick in this area.

L. The south half of this area is underlain generally by massive tonalite and tonalitic gneiss. Bedrock in the north half is predominantly amphibolitic gneiss of greenstone affinity.

Discussion of major gravity gradients and structural breaks

In addition to the distinct gravity gradient associated with the Keweenaw fault, there are other gradients and breaks on the Bouguer gravity map that shed light on the structure of the crust in the Iron River quadrangle. On figure 1b, for example, three lines, (a), (b), and (c) define the position of relatively steep gradients in the gravity data. The west end of gradient (a) coincides with the position of the boundary between greenstone terrane and gneiss terrane as interpreted by Sims (1976) to just north of anomaly G₃. Here, the gradient swings sharply to the north and crosses area L roughly along a boundary that, according to recent unpublished geologic mapping by Cannon and Klasner, separates tonalitic gneiss on the south from denser and more mafic gneiss and amphibolite with greenstone affinity on the north. Although it seems that the greenstone-gneiss boundary should follow this gradient, Sims (1976), on the basis of compelling geologic evidence, has projected it along the Marquette Trough. The evidence include pronounced faulting along the trough plus the fact that rocks on either side of the trough are compositionally different (rocks south of the trough are much more radiometric than they are north of the trough).

The question then remains: what causes this gradient? Past work by Bacon (1964) suggested that the large negative gravity anomaly at E is due to a 3 km thick accumulation of Jacobsville Sandstone. But figure 1a shows that the gradient does not coincide with the contact between Jacobsville Sandstone and Proterozoic X rocks. This suggests that there is a fundamental structural and possibly compositional change in the Archean crust that causes the gradient, and that the large negative gravity anomaly beneath the Jacobsville is not caused by the Jacobsville basin alone. Klasner and Bomke (1977) have suggested that the gradient is caused by lateral structural and compositional variations in the deeper part of the Archean crust.

Gradients (b) and (c) most likely mark the positions of faults. Gradient (b) bounds the north edge of a possible Proterozoic X pluton. Gradient (c) marks a possible fault that truncates the east-west trending basins of Proterozoic X iron-formation G₁ and G₂.

Figure 1b also shows several lines which mark breaks in the gravity data which we call cryptic faults. By breaks, we mean zones or lines along which major gravity anomalies abruptly narrow or are truncated, or where there are abrupt changes in the orientation of elongate anomalies. These breaks are most apparent on a spectrally colored version of the Bouguer gravity map. We think that these breaks may represent faults within Archean basement. Because there are so few Archean rocks exposed in the area relative to other rocks, this fault pattern is cryptic and has not been mapped. The structural fabric expressed by the fault-bounded blocks of Archean gneiss in the southeast corner of the map as well as in area L, however, matches and supports the orientation of the structural breaks.

The gravity model

Figure 3 is a two dimensional gravity model and hypothetical geologic cross section in the western part of the map area. Rock densities used to construct the model were generalized from the density data in Table 2. The aeromagnetic profile, included with the gravity profile, was used as a guide in constructing the crustal model. A portion of the model (A-A') follows one previously constructed by Klasner and Sims (1979) for gravity studies in the Marenisco, Thayer, and Watersmeet quadrangles of western Michigan.

The gravity model shown in Figure 3 provides some valuable constraints on crustal structure in the western part of the Iron River sheet even though there are uncertainties about rock density and bedrock geology is not truly two dimensional along the model. Some important aspects of the model are:

- 1) To account for the large positive gravity anomaly at A on the north end of the gravity model, dense Keweenawan basalt must either be folded or faulted as shown so that it is close to the surface in this area.

- 2) A circular plug, stock, or a zone of felsic rock in Keweenawan basalt beneath the Porcupine Mountain Syncline must be present to explain the -35 milligals gravity low at D on the profile. This was implied by White (1972, page F5) in a longitudinal stratigraphic section drawn to explain stratigraphic relationships in the Keweenawan section.

- 3) The density of the near surface Archean rocks must increase from north to south across the gneiss-greenstone line to account for the positive gravity anomaly just south of the tectonic zone.

- 4) A body of low density material such as granite must be present at location H on the gravity model to explain the relatively low gravity in this area. The Proterozoic X pluton shown beneath the gneiss dome, anomaly J on the model, may be tonalitic-granodioritic gneiss that was formed when Archean crust was remobilized to form the gneiss dome.

Further details concerning the gravity model between A-A' are given by Klasner and Sims (1979).

SOME ECONOMIC IMPLICATIONS OF THE GRAVITY DATA

The positive gravity anomalies at G_1 , G_2 , and G_3 suggests that the iron-formation of unknown character might be present. The east half of anomaly G_1 marks the position of known deposits of iron-formation in the Iron River Syncline. But this map shows that the syncline extends about 20 km west of the mapped syncline thereby increasing the potential for iron resources in this area. Also, the positive gravity anomalies at G_2 and G_3 suggest the presence of buried iron-formation. All three anomalies have associated positive aeromagnetic anomalies as shown in Zietz and Kirby (1971). Anomaly G_2 , however, may be caused by mafic volcanic strata.

The gravity breaks shown on figure 1b may have an important bearing on the economic geology of the area. These features which we believe indicate the presence of fault zones in the Archean basement rocks that most likely influenced structural development and other geologic processes during Proterozoic X and Proterozoic Y and Z time. If the structural breaks do indeed represent major fault zones and zones of weakness as implied in the regional studies by Klasner and others (1979) in the southwestern part of the Canadian Shield, then they most likely have influenced subsequent geologic processes such as sedimentation and the distribution of economically important elements. They also could have served as channelways for migration of hydrothermally circulated fluids and emplacement of igneous bodies. These structural breaks should be considered as regional tectonic guides when interpreting geochemical, geophysical and other geologic data in exploration for mineral resources.

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Table 3.--Brief summary of geologic history, especially tectonic events, that have a direct bearing on the configuration of the Bouguer gravity anomaly surface in the Iron River quadrangle. Data comes from: Klasner and others (1979); Green (1978); Klasner (1978); Sims (1976); Sims and Peterman (1976); White (1966); and Cannon (1973).

Time	Geologic Event	Geologic features and associated gravity expression
1.1 b.y.	Keweenaw rift event: crustal warping and rifting in Lake Superior region; formation of grabens; extrusion of plateau basalt, formation of dike swarms. Subsequent infilling of grabens with thick sequences of clastic sediments.	Thick deposits of basalt have large positive gravity anomalies. A gravity low occurs over a possible volcanic pipe beneath the Porcupine Mountain syncline. Large negative anomalies occur over grabens that are filled with clastic sediments.
1.9 b.y.	Penokean orogeny: multiphase deformation, block faulting and formation of basins and troughs in Archean basement rocks, intrusive and extrusive igneous activity, metamorphism and remobilization of Archean rocks. Troughs and basins in the Archean crust started to form early in the sequence of sedimentation. Volcanism accompanied sedimentation.	Grabens and troughs that have iron-rich beds have positive gravity anomalies. Granite plutons have negative gravity anomalies. Domes of remobilized Archean gneiss have negative gravity anomalies. Generally, volcanic beds have positive anomalies.
2.7 b.y.	Kenoran orogeny closed Archean time. Formation of early crust and multiple periods of orogenesis and tectonism occurred producing in a structurally complex Archean basement that was highly faulted and fractured. These basement faults have been reactivated during subsequent geologic events.	The Zone which divides granite-greenstone terrane on the north from gneiss terrane on the south has, for the most part, an associated north-sloping gravity gradient. Major fracture and fault zones are expressed on the gravity map by abrupt changes in the width of, or changes in orientation of elongate anomalies alone a line. These are called structural breaks in this report.